Analytical Investigation on Efficiency Evaluation of Fibre Reinforced Polymers Confinement on Square Reinforced Concrete Columns

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Fibre Reinforced Polymers (FRP) confinements on square and rectangular sections behave differently from confined circular sections. Confining inward pressure over the entire circular section is uniform, whereas in non-circular sections confining pressure development is inconsistent. As a result, these sections could be divided into the distinct properly and partially confined areas. Presence of these partially confined regions would much reduce influence of FRP confinements to increase concrete's peak strength and ultimate strain. To evaluate confinement effectiveness, effect of mentioned areas must be taken into account precisely. This paper describes a theoretical model adapted to seismic strengthening and retrofit of the square section RC columns confined with advanced composite materials. The model is the author's earlier proposed one calibrated with cautious survey on the existing test data. This model takes into account geometrical parameters of the column shape such as overlapping length and corner rounding radius; furthermore both concrete and FRP confinement mechanical properties. Finally it proposes a new shape factor for the square sections which plays a major role in effectiveness evaluation of FRP confinement.

Keywords: Fibre Reinforced Polymers, square section, Reinforced Concrete columns, strengthening

Recent studies proved that many of the buildings are vulnerable to major earthquakes, despite of the fact that they had been built based on the standards and codes prior to the year 2000 [1, 2]. Precise investigation on the published reports on the functional remained reinforced concrete structures shows that many of damaged structures and buildings had shortage in the transverse reinforcements in columns. Transverse reinforcements, in the shape of the stirrups or spirals, will increase the ductility of the columns, during occurrence of an earthquake, with providing lateral confining stresses.

Over the years, various methods and techniques like jacketing were used to retrofit and strengthen existing buildings. Jacketing techniques were developed to fulfil amplified demand of retrofitting. In this method ordinary materials such as wood, steel and concrete were used to enhance structural behaviour. Researchers suggest section enlargement as one of the other methods for retrofitting [3]. However, section enlargement by means of steel cage or concrete jacketing requires unoccupied space around the columns, which may not be always available due to many reasons, such as architectural limitations. Furthermore, some of the retrofit systems increase weight of the structures, which is not recommended in regions with high seismic hazard.

Confinement via Fibre Reinforced Polymers (FRP) is an efficient, time and cost saving technique to amplify load carrying capacity and ductility of the reinforced concrete (RC) columns with providing high lateral and axial strength in concrete. This strengthening method gains worldwide popularity through few last decades due to outstanding mechanical properties of the FRP systems, as in this case point, their extremely high tensile strength, their significantly low weight to strength ratio, ease in their application to the structural elements and finally their limited need of supporting structures, such as scaffolding. Application of FRP wraps and sheets grant external lateral confining pressure, making the concrete subject to tri-axial state of stress, where maximum attainable compressive strain and strength of concrete will dramatically increase.

Experimental part

So far, numerous models have been proposed to predict the confinement effect on confined concrete strength improvement. Earliest study, performed in University of Illinois, proposed a linear formula in the form of the eq. 1[4]:

$$f_{cc} = f_{co} + k_1 \cdot f_l \qquad (1)$$

In eq. 1, f_{cc} and f_{co} are respectively confined peak and unconfined strength of the concrete. In their study, Richart showed k_1, confining effectiveness coefficient, must have value of 4.1. Since ever, several researchers proposed their models for FRP confined concrete based on the above equation. On the other hand, and in addition to major differences between mechanical properties and behaviour of the steel and FRP (since this model originally developed for steel confined concrete), this formulation cannot be used on the FRP confined sections without appropriate modifications. For circular RC concrete column, different authors suggest values for k_l between 2 and 4 [5 - 7].

Confinement on non-circular sections, such as square and rectangular ones, acts in partially distinct ways. High stress concentration on the sharp corners may lead to premature rapture of the FRP wraps, before development of their full confining action. Moreover, recent studies uncovered those geometrical parameters of the section might affect confining contribution of the FRP wraps [8]. Besides, a comprehensive accepted model for estimating peak confined concrete strength in square and rectangular sections is still unavailable. Principal aspiration of this paper is to modify authors formerly proposed model. Recent model estimates the peak strength of the confined RC square section taking into account the failed parameters to spot, such as bond length of the FRP wraps around the column.

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Proposed model

Previous studies by different researchers showed that in contrast with circular and elliptical members, FRP confined elements with square and rectangular cross sections are not uniformly confined. Presence of unconfined and partially confined sections will significantly reduce the confining effectiveness in these members. Practical results illustrated that unconfined areas will develop in the middle of the section sides; where confining action has its least value. If the member is reinforced with steel bars, confining effect of internal reinforcing must be considered too, on the ground of the fact that transverse reinforcements such as stirrups provide confining stress on the section core.

Suggested model in this paper is the modified version of formerly proposed model in [9]. In this study, to improve observed deficiencies in the preceded model, wider span of experimental data with various corner radii (ranging from 5^{mm} to 50^{mm}) are considered. Figure1 presents a typical RC member with square cross section confined with FRP sheets. As illustration depicts, parts of the section are confined with FRP resulting confining stress (dashed), whereas some other areas are affected with internal steel confining stress (dotted) and finally, remaining parts of the section are unconfined.

FRP confined area
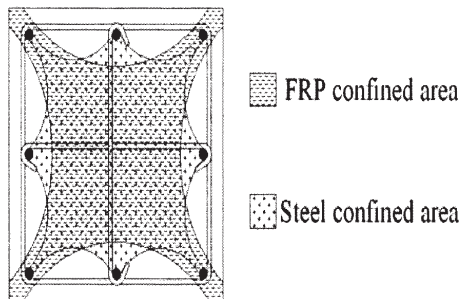
Steel confined area

Figure 1. Effective area of each confining device on a typical Square RC section

Contribution of the stirrups in providing confining stress on the section core as explained in [10] depends on the spacing and mechanical properties of both stirrups and longitudinal reinforcements. In most of the existing models $f_{l,frp}$, FRP developed confining pressure, estimated from eq. 2:

$$f_{l,frp} = 0.5\rho_j E_j \varepsilon_{ju} \qquad (2)$$

Where E_j and ε_{ju} are Elastic modulus and Nominal ultimate tensile of wraps, respectively and ρ_j is FRP volumetric ratio. However, authors demonstrate that confining effectiveness in a square section depends on the area of the confined segments with FRP, overlapping length of wraps and finally, section shape factor, K_s. In order to acquire shape and magnitude of the confined areas and with respect to bi-axial symmetry of the square section, quarter of the section is exhibited in figure 2.

It is assumed that confined and unconfined areas detaching lines are second order parabolas, whose coefficients are calculated from geometrical boundary conditions in the section. Detailed calculations are specified elsewhere in [8, 9]. With notations on this figure, formulations of these parabolas are:

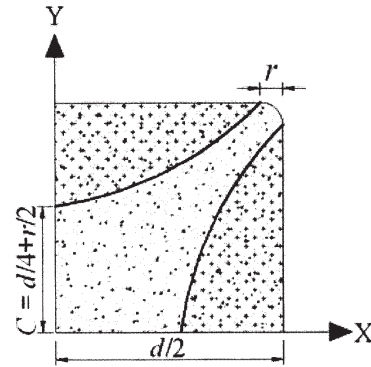$$y = \frac{1}{d-2r} \cdot x^2 + \frac{1}{2} \cdot \left(\frac{d}{2}+r\right) \qquad (3)$$

Fig. 2. Quarter of a square section, unconfined areas are hatched

Confined Areas and Shape Factor

Corner rounding will reduce cross section area. After rounding, remaining gross area, A_g, would be:

$$A_g = d^2 - (4-\pi)\cdot r^2 \qquad (4)$$

Each unconfined segment of the section has the area of $0.166(d-2r)^2$. With deducting these four portions from gross section, FRP confined area of the section would be calculated using eq. 5:

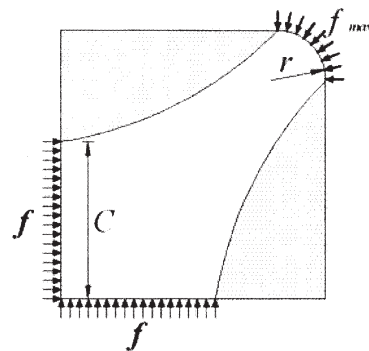$$A_{con} = 0.333\times(d^2 + 8dr - 10.575\cdot r^2) \qquad (5)$$

Fig. 3. Forces acting on the section quarter

Acting forces on the confined section are demonstrated in figure 3. If we consider either horizontal or vertical equilibrium, it is easily achieved that:

$$\frac{f}{f_{max}} = \frac{r}{C} \qquad (6)$$

Where f is assumed to be FRP inward stress exerts on the confined parts of the section. Moreover, eq. 6 reveals that stresses on the confined parts of the section are fraction of the maximum available confining stress at the rounded corner, f_{max}. In this manner, section shape factor, K_s, introduces as:

$$K_s = \frac{r}{C} \cdot \frac{A_{con}}{A_g} = \frac{4r}{d+2r} \cdot \frac{A_{con}}{A_g} \qquad (7)$$

Hoop Rupture Strain

Documented results demonstrated that curvature of the FRP warps will have great effect on its behaviour. Measured failure strain of the FRP materials in many experimental tests varies with obtained values from FRP coupon tensile tests. A lecture survey by [11, 7] on the specimens confined with FRP layers indicates that ultimate tensile strain, for CFRP materials, could be expressed more or

SUMMARY OF THE CALCULATED RESULTS FOR THE AVAILABLE
EXPERIMENTAL RECORDS

Rochette et al (2000) Tests results						
(1)	(2) mm	(3) mm	(4) MPa	(5) MPa	(6) MPa	(7) MPa
S5-C5	152	5	43.9	43.90	0.28	45.80
S25-C3	152	25	42	41.58	1.11	49.22
S25-C3	152	25	42	43.26	1.11	49.22
S38-C3	152	38	42	47.46	1.77	53.18
S38-C3	152	38	42	50.40	1.77	53.18
S25-C4	152	25	43.9	50.92	1.48	53.38
S25-C4	152	25	35.8	52.27	1.48	45.12
S25-C5	152	25	43.9	47.85	1.85	55.53
S25-C5	152	25	35.8	57.64	1.85	47.21
S38-C4	152	38	35.8	59.43	2.36	50.01
S38-C5	152	38	35.8	68.74	2.96	53.02

Al-Salloum (2007) Tests results						
(1)	(2) mm	(3) mm	(4) MPa	(5) MPa	(6) MPa	(7) MPa
S-r 25	150	25	31.82	48.25	3.41	50.86
S-r 25	150	25	28.5	45.59	3.41	47.15
S-r 38	150	38	27.7	56.96	5.46	54.33
S-r 38	150	38	30.29	54.96	5.46	57.54
S-r 50	150	50	26.72	61.67	7.19	58.79
S-r 50	150	50	28.26	63.68	7.19	60.89

less 0.6 times of the nominal ultimate value. In the recent studies, authors spotted that maximum achievable tensile strain of the wraps directly relates with overlapping length of the FRP materials; enhancement in overlapping length will amplify attainable tensile strain. Owing to the fact that diverse values of the overlapping length have been used in various experiments, it seems rational to express this length as a portion of the section side length. For this purpose, a survey has been done on the available results of the CFRP wrapped specimens, with respect to their overlapping length, l_o, to examine proposed idea. It concludes that overlapping to side length ratio, is effecting on the maximum hoop rupture strain with order of two. In this manner, maximum hoop rapture strain can be express as follows:

$$\varepsilon_{h,rup} = 0.65 \times (l_o/d)^2 \cdot \varepsilon_{uj} \qquad (8)$$

In order to attain convincing results for the confined peak stress, authors modified eq. 2 into the following form:

$$f_{l,frp} = 0.5 \rho_j E_j K_s \varepsilon_{h,rup} \qquad (9)$$

The researchers proposed an equation to predict confined concrete peak stress [12]. With substituting FRP confining stress in this equation; we will reach the following expression:

$$f_{cc} = f_{co} \cdot \left(2.254 \times \sqrt{1+7.94 \cdot (f_{l,frp}/f_{co})} - 2(f_{l,frp}/f_{co}) - 1.254\right) \qquad (10)$$

Survey Study

In order to find the hoop rupture strain as a fraction of the ultimate tensile strain, experimental results were compared to each other [13-16]. First group of the specimens had overlapping length equals 100 mm, however overlapping length of the second surveyed group was 150 mm. Summary of this survey is represented in the table 1. Columns (1) and (2) introduce specimen name and side length, respectively. Corner rounding radius for each specimen is shown in the column (3). Unconfined concrete strength and maximum recorded confined compressive strength of specimens are presented in columns (4) and (5). Resulted confining stresses from eq. 9 are depicted on the column (6). At the last step, calculated confined peak strength of the specimens is demonstrated on the column (7) using eq. 10.

Calculated values are compared with experimental results from figure 4. In this figure, horizontal axis represents confinement ratio, $f_{l,frp}/f_{co}$. Vertical axis is concrete compressive peak stress due to the provided lateral confining from FRP sheets. Total Mean Error (ME) between estimated and recorded results was 1.2 percents (10.6% for Rochette and -9.4% for Al-Salloum test). All in all, calculated values were closer to the experimental acquired values in Al-Salloum test. Furthermore, in Rochette et al. test, theoretical and experimental values are more coincident on the low level confinement ratio. Amplified bond length will delay failure of the FRP materials around the square section and provide higher confining ratio, as is illustrated on the figure 4 for Al-Salloum test results.
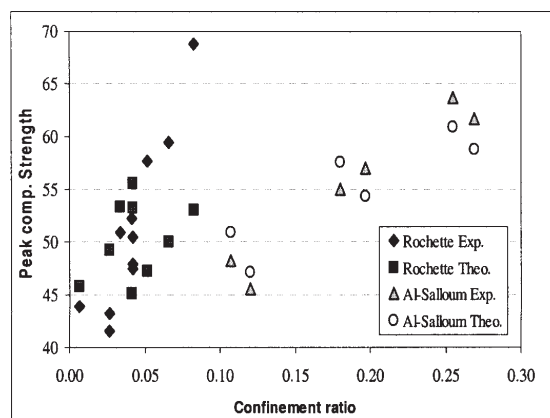

Fig. 4. Experimental vs. Analytical results for the survey study

Conclusions

Confining via FRP is an appropriate method to increase strength of RC square columns. The effectiveness of this technique can be influenced by ratio of confined to unconfined areas, radius of corner rounding and provided overlapping length of the wraps.Outcome of these parameters are introduced as a new shape factor. Both experimental and analytical results show that increase in the shape factor and overlapping length will lead to improvement of the lateral confining stress. As a result, maximum compressive strength of the concrete will enhance. Proposed model considers all of the mentioned matters in predicting compressive peak stress of confined concrete. Evaluation of theoretical results with available experimental records shows satisfactory conformation with an acceptable error boundary. To increase accuracy of this model, next step would be finding the optimum

bond length for FRP wraps, which beyond this length additional overlapping have no positive effect. Further comparison with larger database of tested RC square columns is recommended for more accurate judgment on described model.

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